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DESIGNING LOW AND ZERO CARBON PRODUCTS AND SYSTEMS: IMPROVEMENTS BASED ON CONSUMERS' EXPERIENCE OF ADOPTION AND USE

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ABSTRACT

The development and rapid consumer adoption of low and zero carbon (LZC) technologies are key elements of UK and EU carbon reduction strategies to meet the challenge of climate change. Many LZC technologies are available, ranging from established energy efficiency products such as home insulation and energy-efficient lighting to more innovative renewable energy systems, including solar thermal systems, micro-wind turbines, solar photovoltaics and biomass stoves and boilers. This paper examines key influences on consumer adoption – and non-adoption – of energy efficiency products and renewable energy systems based on the findings of a UK Open University project, which conducted some 90 in-depth telephone interviews plus an on-line survey with nearly 400 responses during 2006. The survey results show that it is important to research consumer requirements and use behaviours when developing 'green' technologies. Consumer adoption of LZC products and systems has been relatively slow and, even when installed, due to behavioural effects, they have not always reduced carbon emissions as much as expected.

The results of this study of UK consumers' experiences shows that improved designs are required to address barriers to LZC adoption and problems in use, including functionality, ergonomics, interconnectedness with other systems and symbolic value, as well as cost and payback. Offering challenges for designers and engineers and marketers, the paper identifies user-centred ideas and concepts to promote more rapid adoption and carbon-saving use of LZC technologies.

Keywords: low and zero carbon (LZC) technologies, energy efficiency, renewable energy, consumer surveys, user-centred design

1. INTRODUCTION

In order to tackle climate change the UK Government set a target of reducing the nation's carbon emissions by 60% from their 1990 levels by 2050 and is expected to exceed its Kyoto Protocol commitment to reduce greenhouse gas emissions by 12.5% between 2008 and 2012 [1]. The development and rapid consumer adoption of low and zero carbon (LZC) technologies to reduce the 28% of UK carbon emissions from homes are key elements of the Government's climate strategy [2].

Many LZC products and systems are now available, ranging from established energy efficiency measures, such as home insulation, heating controls and energy-efficient lighting, to more innovative renewable energy technologies, including solar thermal systems, micro-wind turbines, solar photovoltaics (PV) and biomass stoves/boilers. Consumer adoption of these LZC products and systems has, however, been slow. For example, about 60% of the 25 million existing UK homes could benefit from new or increased loft insulation to the 270mm thickness required for new dwellings, which it is estimated would save 1.28m tonnes carbon per year [3]. Solar thermal water heating systems which in Britain typically provide about 50% of a household's annual hot water demand are still rare; with only 78,500 installations, 0.4% of the potential 19 million suitable UK homes [4]. It is estimated that installing solar water heating systems in these homes would save 1.7m tonnes carbon per year [5].

There is already a considerable body of work on the factors that influence consumer adoption of energy efficiency measures [6]. For example, the UK Government's Energy Efficiency Action Plan stated, '*in the household sector, there are different barriers to improving energy efficiency, and three predominate: lack of information, high upfront costs, and hassle and disruption*' [7]. Less is known

about drivers and barriers to consumer adoption of renewable energy technologies. One survey of enquirers to a solar water heating (SWH) promotion scheme in London with 380 responses showed that the main drivers for installing SWH systems were environmental concern and saving money, while the main barriers were capital cost and lack of trustworthy information or reliable brands [8]. However, merely persuading people to adopt LZC products or systems does not guarantee reduced carbon emissions, since consumers often cancel out the benefits by increasing consumption, or simply not using LZC technologies as expected. For example, many people waste fuel because they fail to understand, or could not be bothered, with heating controls such as thermostatic radiator valves or central heating programmers [9]. In the case of gas powered micro-CHP, although laboratory tests suggest that the units should reduce carbon emissions compared to a condensing boiler and grid supplied electricity, a programme of field trials indicate micro-CHP performance is not as encouraging as had been hoped. About a third of the installations appear to reduce emissions and about a third increases them, with the remainder showing no discernable difference. It seems likely that this is due to the intermittent heat demand of real households, which reduces the efficiency of the units [10]. Existing research has tended to focus on non-technical financial and market drivers and barriers to consumer adoption of LZC technologies. Less is known about the influence on consumer adoption of the design and technology of the LZC products and systems themselves, or how people use the technologies after adoption. One reason is that LZC products and systems often seem to have been designed as functional energy saving devices without taking sufficient account of consumer requirements and use behaviours. *‘Does the engineer forget the user?’* asks Knut Holt, arguing that users are often neglected in engineering product design [11]. For example, compact fluorescent lamps (CFLs) have taken many years to achieve only limited penetration into UK homes, even when subsidised to reduce their purchase price. This appears to be because of issues such as their size and shape, incompatibility with existing light fittings and their colour temperature, compared to incandescent light bulbs. Then when installed people may leave CFLs switched on longer because of their efficiency, warm-up time or fears of shortening life, or install additional lighting in the home or the garden because it is energy efficient. Such ‘rebound’ effects reduce the effectiveness of LZC technologies such as CFLs in saving energy and reducing emissions [12]. The Open University Design Innovation Group’s research project ‘People-centred ecodesign’ aimed to research the technical and non-technical factors influencing consumer adoption – and non-adoption – of energy efficiency products and renewable energy technologies. The research also aimed to find out what consumers want from these LZC technologies, how people actually use them and their ideas for improving them, in order to identify requirements and design challenges for more user-friendly and desirable products and systems.

2 METHODOLOGY

What methods could be employed to research these topics? Given the range of technologies concerned, from simple home insulation products to domestic renewable energy systems, it was not possible within the time-scale of the project to employ user-centred design techniques such as focus groups, consumer evaluations of simulations, mock-ups or prototypes, and observation of the products or systems in use. Instead a two stage survey approach was used, based on methods employed for user needs assessment for product development and innovation [13].

In the exploratory phase, we first conducted in-depth interviews with volunteer consumers to gain insights into the factors influencing the adoption, non-adoption and use of a range of LZC technologies, including insulation, heating controls, condensing boilers, CFLs, solar thermal and solar photovoltaic systems. Second, we carried out a literature review and discussions with professionals in the field of energy efficiency and renewable energy, to identify further issues affecting consumer adoption and use, plus ideas for improving the uptake of LZC products and systems. Third, we conducted an internet survey of 50 energy professionals to evaluate the improvement ideas and generate further ideas that would facilitate consumer adoption and effective use of LZC technologies. These exploratory studies were used to develop a model of consumer adoption and use of LZC products and systems. The model identified four sets of factors that influence adoption decisions and use behaviours. Three sets concerned non-technical factors; namely, the socio-economic context (e.g. fuel prices), consumer variables (e.g. attitudes) and communication sources. One set concerned the design and technology of the product or system itself; namely, its functional utility (performance, ease of use, safety, reliability, etc.), its interconnectedness with other systems (buildings, heating systems,

etc.), symbolic value (image, appearance, novelty, etc.), plus its price [14]. The model together with the improvement ideas from the exploratory study helped develop the interview schedules and an online questionnaire to survey consumers for the main phase of the research.

2.1 The sample

For the main phase the research team conducted some 90 in-depth telephone interviews: (a) with clients of two UK Energy Efficiency Advice Centres (EEACs) who had adopted, or considered but rejected, loft insulation, heating controls, a condensing boiler, and/or energy efficient lighting; and (b) with people seeking advice from a renewable energy charity, the National Energy Foundation, on solar water heating. An on-line questionnaire linked to the websites of a 2006 BBC TV series on climate change and the UK's official domestic energy advice body, the Energy Saving Trust, produced 390 responses from consumers who had adopted – or considered but rejected – one or more of the above energy efficiency measures, and/or renewables, including solar water heating, solar photovoltaics, micro-wind turbines and wood burning stoves [15].

The respondents to the on-line questionnaire were self-selected and not unexpectedly were 'greener' and from higher socio-economic groups than the general UK population. Most online respondents said that they were concerned about the environment, recycled their household waste and tried to save on energy, water and car use. The people we interviewed claimed similar levels of 'greenness'. This is therefore a 'purposive' rather than a representative survey, needed when obtaining information and feedback from early adopters of new technologies such as household renewables [16], and to a lesser extent also for energy efficiency measures, many of which are still at the early adoption stage in the UK. Our respondents' reasons for non-adoption, and the problems of adopters, thus represent significant barriers that need to be addressed before the less wealthy, less 'green' general population will start adopting LZC technologies in significant numbers. Our main results are given in separate sections on energy efficiency and renewable energy technologies below.

3 ENERGY EFFICIENCY TECHNOLOGIES

Most UK homes have one or more energy efficiency measures, but there is great scope for improvement, as UK housing is one of the least energy efficient in Europe. For the surveys we chose cost-effective measures for improving home energy efficiency that involved at least some post-installation interaction with users. Table 1 shows the numbers adopting, and considering but rejecting, the energy efficiency measures we investigated.

Table 1. Adoption and non-adoption of one or more energy efficiency measures

<i>Energy efficiency measures</i>	<i>Installed* (on-line survey)</i>	<i>Installed (interviews)</i>	<i>Considered but decided against* (on-line survey)</i>	<i>Considered but decided against (interviews)</i>
Loft insulation	229 (59%)	28	59 (15%)	7
Timer/programmer	286 (73%)	21 (either timer or TRV)	13 (3%)	0
TRVs	214 (55%)		53 (14%)	0
Condensing boiler	109 (28%)	7	97 (25%)	0
CFLs	275 (71%)	17	23 (6%)	3
LED lighting	28 (7%)	0	62 (16%)	0

** Total on-line responses, including energy efficiency measures + renewables = 390*

3.1 Adoption, use and improvement of energy efficiency technologies

The adopters of energy efficiency measures do so for many reasons; but in the on-line survey the most frequently reasons cited by the adopters of loft insulation, timer/programmers condensing boilers and CFLs were: saving energy; reducing fuel bills and concern for the environment. In the following sections we look in more detail at these drivers, together with the barriers to adoption, the benefits and problems experienced by users, and ideas for improving these technologies to increase their uptake.

Loft insulation

The majority of our on-line survey respondents installed loft insulation (LI) to save energy (84%) and/or fuel bills (81%) and/or to have a warmer home (77%). Over two thirds (68%) also responded that they installed LI to reduce environmental impacts; a driver dependent on this group's green attitudes. The interview sample was less green, most installing LI to save money and for warmth, with only 21% adopting for environmental reasons.

Other reasons for adoption were that loft insulation is a zero maintenance product (35%), can be installed as a do-it-yourself job (30%) and/or as part of other home improvements (23%).

Relatively few on-line respondents (15%) seriously considered but rejected loft insulation, mainly because of losing loft storage space (37% of non-adopters), a barrier to do with the interconnectedness of insulation with other building elements. Nearly a third of non-adopters would have installed LI given a better post-insulation storage system. In the open comments a few adopters and non-adopters mentioned they were deterred by the irritant effects of the glass or lava fibre normally used for loft insulation, some mentioning their preference for eco-friendly materials such as recycled paper.

Over half (58%) of adopters said the main benefit of loft insulation was a warmer house, while nearly a third said they also had lower fuel bills (29%) and/or energy consumption (31%). These results typify the well-known 'rebound effect' of home insulation, where adopters take some or all the benefit in higher room temperatures, heating more of the house or for longer periods. Five respondents mentioned that loft insulation also helped keep their home cooler in summer; likely to become increasingly important with climate change, but not generally mentioned in insulation programmes.

These barriers and problems experienced by users suggest several improvement ideas and design challenges, many already identified in the exploratory survey of energy professionals. On-line respondents and interviewees were asked to respond to a list of possible improvements (generated by the research team following the exploratory survey of energy professionals) and also to suggest their own ideas. Table 2 shows loft insulation improvements that many on-line survey adopters and non-adopters thought were good ideas and would encourage adoption.

Table 2 Loft insulation – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=237</i>	<i>Non-adopters (%) N=59</i>
Thinner/less bulky insulation materials	143 (60%)	29 (54%)
Systems to provide storage space above LI	93 (39%)	17 (31%)

In addition some survey respondents suggested solution concepts including:

- a demountable loft storage platform, with optional storage boxes;
- pre-insulated loft boarding for DIY installation;
- insulation material pumped into spaces under loft boarding (like cavity wall insulation).

Post-insulation loft storage clearly needs a better solution than those currently available; a professional task of raising the joists and boarding or individual 'bodged' solutions. Some solutions e.g. pre-insulated boarding is available to the professional but not the DIY user. Other worthwhile innovations such as under-floor insulation (for retrofitting in lofts and other areas) remain to be developed [17]. LI also offers challenges for materials innovation. Over half of the non-adopters said that non-irritant, eco-friendly and/or higher performance, less bulky insulation materials would have encouraged them to install. Such insulation materials (e.g. Aerogels, multi-layer thermo-reflective sheeting) have been developed but because of their cost and/or performance are not available in UK subsidised schemes. Desirable innovation could thus focus on improvement and cost-reduction of high performance insulation materials.

Central heating controls and condensing boilers

Over 90% of UK homes have central heating, mainly from a gas-fired boiler and radiators plus one or more controls, such as thermostatic radiator valves (TRVs). Under 2005 UK Building Regulations new or replacement boilers must be high efficiency condensing designs, which if installed in 17 million suitable homes would save about 7% of household carbon emissions [18]. With increased boiler efficiencies effective controls are relatively more important. If people used existing controls

properly estimates are that about 3% of UK heating energy consumption could be saved, while installing improved controls could save about 1% of UK household carbon emissions [19].

Most of our on-line respondents installed timer/programmers (TPs) and/or TRVs to reduce energy consumption (78% and 57% respectively) and/or their fuel bills (74% and 59%). A smaller number (57% and 45%) claimed that they installed these controls to reduce environmental impacts. However, some respondents seem to be referring to controls they already possessed.

Condensing boilers were installed for similar reasons – saving energy (77%), money (69%) and/or the environment (60%) – but the main driver was often that an existing boiler needed replacing (60%). As condensing boilers are now virtually mandatory in the UK, the barriers to installation since 2005 apply to early replacement of conventional boilers. Unsurprisingly, the majority (70%) of non-adopters of condensing boilers both pre- and post-2005 considered them too expensive. Other deterrents to adoption include the shorter life expectancy of condensing boilers (43%) associated with a reputation for unreliability that affected early designs introduced into the UK.

About 40% of the on-line adopters of heating controls and condensing boilers noticed reductions in fuel bills and/or energy consumption, but a third also noted a warmer house and a quarter (23%) of users admitted they took the main benefit of new controls in additional heating or hot water, suggesting some rebound effects not normally associated with these technologies.

A few users (9% of on-line heating control adopters) find electromechanical timers fiddly to adjust, others (11%), especially the elderly, find electronic programmers with tiny buttons and LCD displays difficult to see and too complex to understand. Adopters also mentioned difficulties using TRVs with their small markings, unrelated to room temperature, that need to be set on each radiator by trial and error. Such problems often mean that controls were rarely adjusted or simply not used.

These drivers, barriers, problems and benefits suggest some improvement ideas and design challenges. Nearly half (46%) of non-adopters of condensing boilers would like more durable designs, while about half of adopters (52%) and a third of non-adopters (32%) would like to see the boiler's working efficiency displayed. However, this innovation could increase product complexity and costs when the main challenge for condensing boiler design is to further improve durability and reduce costs.

For heating controls, over half of adopters agreed with or mentioned one or more of the following as good ideas: controls that automatically optimise comfort and energy use; provide feedback on energy consumption, are designed for all users (including the elderly and disabled); display room-based heating times and temperatures; and detect where heating is required (Table 3). A quarter to a half of non-adopters said these improvements would encourage them to install new controls.

Table 3 Controls – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=282</i>	<i>Non-adopters (%) N=30</i>
Heating controls designed for all users	158 (56%)	10 (33%)
Controls that respond to room use and detect where heating is most required	154 (55%)	13 (43%)
Controls that operate automatically to optimise comfort and save energy	144 (51%)	12 (40%)
Controls that display set heating times and temperature for each room	148 (52%)	10 (33%)
Controls with feedback on money and energy used/saved	150 (53%)	11 (37%)

Such responses suggest that there could be a demand for 'inclusively' designed, intelligent heating controls that provide feedback and operate automatically, but with manual over-ride.

More innovative concepts suggested by our respondents included:

- central heating controls that can be adjusted remotely via a portable device or the internet,
- TRVs that can be calibrated for set temperatures, perhaps with child locks.
- A computer program to enable users to control their heating to optimise comfort and energy use taking into account the characteristics of their dwelling, heating system and needs.

While some of these user ideas and specifications have been incorporated in heating control designs, mainly for non-domestic applications, there is scope for some to be employed for the development of

intelligent domestic central heating controls, perhaps as part of home networking systems. Such home networks for controlling lights, appliances, etc. could save 0.4m tonnes carbon per year by 2020 [20] and could provide sufficient advantages over existing controls that consumers will decide to adopt them rather than rely on their old heating controls when installing a new a heating system.

Energy-efficient lighting

Energy efficient lighting includes compact fluorescent lamps (CFLs) and emerging technologies such as Light Emitting Diodes (LEDs). In 2000, about a quarter of UK homes owned at least one CFL [21]. The ownership percentage is now greater and it is estimated that widespread adoption of CFLs for lighting could save about 1.5% of UK household carbon emissions [22].

About 70% of on-line respondents had installed at least one CFL to save energy (91%) and/or reduce fuel bills (82%) and/or for environmental reasons (82%). Only 6% had considered CFLs but decided not to get any. The biggest deterrent was their size and perceived ugliness (42% of non-adopters), followed by their cost, incompatibility with existing shades and fittings and/or dimmers and/or their light quality (all 33%). These are barriers that involve interconnectedness with existing products and home interiors. These barriers also stopped adopters from installing additional CFLs in certain locations, with complaints about size and/or shape (41%), warm-up time (34%), incompatibility with light fittings (29%) and dimness (26%). However, these responses indicate that many didn't realise that CFL design and technology had improved considerably since their first introduction.

About a quarter of CFL adopters in the on-line survey noticed reduced electricity bills. Nevertheless, there were limited rebound effects, as about 10% of users chose to leave CFLs switched on longer than incandescent lamps and/or installed additional CFL lighting in the home, in the garden or for security. One adopter stated *'I now leave a light on in the hallway all day so that I don't have to come home to a dark house. I am also happy to leave the landing light on all night for my son. I would still prefer not to have the lights on all day, but feel better that the lights are energy efficient.'*

The improvements respondents most often wanted were smaller, even more efficient CFLs in various shapes compatible with existing fittings, especially halogen spotlights and dimmer switches (Table 4). Although manufacturers have introduced many of these innovations, the non-standard CFL designs e.g. spot-lamps, miniature lamps, dimmable lamps, etc. are only available from specialist suppliers. It is not surprising therefore that most consumers (and as our exploratory survey indicated, also many energy professionals) are unaware of their existence.

Table 4 CFLs – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=266</i>	<i>Non-adopters (%) N=24</i>
CFLs that fit existing light fittings	191 (72%)	11 (45%)
Different colour rendering	111 (42%)	11 (45%)
CFLs that can be dimmed	147 (55%)	10 (42%)
More powerful CFLs (e.g. 150 watt equivalent)	108 (41%)	6 (25%)
Wider range of lamp fittings for CFLs	106 (40%)	8 (33%)
Even higher energy efficiency	171 (64%)	7 (29%)

A few (7%) respondents had installed light emitting diode lamps, or considered but rejected them (16%). The main driver for adoption was saving energy (57% adopters), but only half (51%) were satisfied with their purchase. The main problems, experienced by about 20% of LED adopters, concerned cost and insufficient brightness, making LEDs suitable only for (additional) decorative lighting. One user stated *'LED's provide excellent background and decorative lighting... ideal for watching TV, although you can just about read with the LEDs'*. The main improvements wanted included LEDs suitable for general lighting. Given the lower energy consumption per unit of light output and much longer life of LED lighting compared to CFLs, this technology has great potential for reducing carbon emissions; one estimate is 0.3m tonnes carbon per year by 2020 from households alone [23]. The development of LEDs for general lighting thus provides an important technical challenge for engineers and manufacturers.

4 RENEWABLE ENERGY TECHNOLOGIES

In the UK in 2005 there were some 82,200 domestic micro-generation and renewable energy systems, with solar water heating (SWH) accounting over 95% of them [24]. Even rarer are domestic micro-generation/renewable energy technologies, including ground source heat pumps, wood pellet stoves and boilers, solar PV and micro-wind. It is estimated that there were only 3750 such systems in 2005 in the UK; so as expected there were only a few adopted by our respondents. However, a surprising number of on-line respondents claimed to have seriously considered one or more of these technologies but decided against adoption.

Table 5 provides details of the numbers adopting, and considering but rejecting, one or more of the renewable energy technologies in our surveys.

Table 5. Adoption and non-adoption of one or more renewable energy technologies

<i>Renewable energy technologies</i>	<i>Installed (on-line survey)</i>	<i>Installed (interviews)</i>	<i>Considered but decided against (on-line survey)</i>	<i>Considered but decided against (interviews)</i>
Solar water ht	39 (10%)	15	151 (39%)	13
Photovoltaics	12 (3%)	0	130 (33%)	0
Micro-wind	7 (2%)	0	128 (33%)	0
Wood stove	63 (16%)	0	65 (17%)	0

Note: Total on-line responses, including energy efficiency measures + renewables = 390.

(Adoptions or non-adoptions of renewables are percentages of total responses)

4.1 Adoption, use and improvement of household renewables

Adopters of renewable energy systems do so for many reasons. In the on-line survey reducing fuel bills, saving energy and concern for the environment were the reasons most frequently cited by SWH adopters. For wood burning stoves these drivers are important, but the stoves are mainly bought by people wanting the warmth and appearance of a real fire. For solar PV, environmental concern, and for micro-wind, saving energy, were the main drivers for adoption.

In the following sections we look in more detail at these drivers, together with the barriers to adoption, the benefits, problems experienced by users, and ideas for improving these technologies.

Solar water heating

SWH systems are commonplace in many countries, but are still rare in Britain. In our on-line sample SWH was the most commonly adopted renewable energy technology with 39 installations (10% of the sample) a reflection of its greenness. We also conducted 15 interviews with SWH adopters.

The main reasons for installing SWH were to save energy (83% of on-line adopters), reduce environmental impacts (79%) and reduce fuel bills (77%). Another frequent reason (42%) was having available funds – SWH adopters were often retired (45% interviewees and 18% on-line respondents) and willing to invest in a green, money-saving system. Another common reason for adoption, given by three quarters of our interviewees, was seeing working systems in friends', relatives' or neighbours' homes. The reasons were thus a combination of green attitudes, disposable cash and interpersonal communications.

Overall two-thirds (67%) of on-line and nearly half (47%) of interviewed SWH adopters were satisfied with their system. The benefits included lower fuel bills (54% adopters) and energy consumption (46%). However, the most frequent response (65%) was the pleasure of using solar heated water, and half the users tried to use it when available, for example, showering in the afternoon.. The most frequent disappointment was not being able to use solar heated water in the dishwasher or washing machine (31%); due to plumbing constraints or because most new appliances are cold-fill only – problems of interconnectedness. Most interviewed adopters experienced problems with leaks, pumps and valves (80%), monitoring gauges and adjusting valves to prevent overheating (60%), insufficient storage capacity for sunny days and difficulties of understanding the controls and operating the system to minimise back-up water heating. One adopter complained '*The main problem is we don't know how*

much solar heated water the system produces. It would be nice to be able to switch the immersion heater off during suitable days and to know that all hot water is free, in theory’.

A significant proportion (39%) of on-line respondents had seriously considered but decided against getting SWH. The overwhelming reason was capital cost (73%), but other reasons were also mainly cost related; namely likely inadequate fuel savings and payback given uncertain reliability and system life (up to 36% non-adopters).

As before, these barriers and, problems suggest some improvement ideas and design challenges. Adopters and non-adopters both in the on-line survey and interviews agreed with or mentioned similar SWH improvement ideas (Table 6). Not surprisingly, both groups would like lower cost systems, perhaps using simpler technology. For instance a ‘solar lilo’ was mentioned, but such ideas would only work in areas receiving high annual solar radiation.

Table 6 Solar water ht – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=52</i>	<i>Non-adopters (%) N=149</i>
Lower cost SWH systems	23 (44%)	89 (60%)
Solar panels integrated with the roof	36 (69%)	72 (48%)
Packaged systems e.g. SWH plus boiler	25 (48%)	64 (43%)
Installation of solar panels from inside the house	23 (44%)	44 (30%)
System designed to give user feedback	29 (56%)	61 (41%)
Improved visual appearance of solar panels	14 (27%)	34 (23%)

Percentages are of on-line respondents who answered at least some questions on SWH

More adopters, having experienced SWH, felt that systems integrated with the roof and/or involving installation from inside the house and/or which give feedback on money and energy saved were good ideas. The latter idea reinforces the demand for more informative and easier to understand SWH controls. A few respondents were aware of more technically advanced SWH systems available in other countries such as Germany, including systems with controls linked to internet weather forecasts to inform the user when solar hot water was likely to be available. More adopters than non-adopters would like to see integrated systems, e.g. a SWH and condensing boiler package such as offered by one major manufacturer. Such systems could help avoid interconnectedness problems such as experienced by one interviewee who installed a combination boiler (which does not require a hot water tank) not realising it was incompatible with SWH. Other ideas and concepts suggested by respondents included:

- A diagnostic system to warn about component failure and to locate leaks in pipes. With existing controls, users are often unaware if their SWH system is not functioning.
- Larger, better insulated tanks to store hot water for days when the system is not collecting solar energy. Larger storage tanks might be possible if a pumped system was developed that allowed the tank to be located in the loft rather than in airing cupboards etc. as is usual in the UK.

Micro-wind

Micro-wind turbines with outputs of 0.5kW to 6kW are established products for remote use on farms, boats, etc. However, 1kW to 1.5kW grid-connected household micro-wind turbines are an emerging technology being sold to UK consumers to generate an estimated 10% to 30% of domestic electricity, but with unproven performance in urban and suburban areas. Indeed many engineers are very sceptical about the value of these micro-wind systems, given that the power output of a wind turbine is proportional to its swept area and the cube of the wind speed and that air turbulence around buildings greatly reduces useful wind speeds. Hence estimates of micro-wind’s carbon saving potential vary widely or are not stated [25].

Only seven people in our on-line survey had installed a micro-wind turbine, two-thirds saying they did so mainly to reduce mains electricity consumption. Three reported being satisfied with their system and only one was dissatisfied; even the person whose turbine was destroyed in a lightning strike would still recommend micro-wind to anyone living in a suitable area. Other problems mentioned included that wind-generated electricity was not always available when required.

A third of on-line respondents said they had seriously considered this technology but rejected it. The main barriers to installation were cost (mentioned by 53% of non-adopters) and long payback. The other main deterrents included finding a suitable location for the unit (33%); noise/vibration (26%); unattractive appearance (22%); uncertainty about this new technology's performance and reliability (21%); and problems connecting to existing electricity systems (21%). Many considered towns and cities unsuitable for micro-wind because of worries about noise and visual intrusion, with one non-adopter saying '*I live in a suburban area: imagine if everyone had one! Chaotic visual impacts and noise pollution*'.

Table 7 Micro-wind – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=18</i>	<i>Non-adopters (%) N=126</i>
Lower-cost micro-wind systems	12 (67%)	103 (82%)
Wind turbine(s) integrated with roofing.	9 (50%)	76 (60%)
Gives user feedback on money and energy saved	6 (33%)	53 (42%)
Visually attractive wind turbine	6 (33%)	38 (30%)

Percentages are of on-line respondents who answered at least some questions on MWT

Again, these drivers, barriers, problems and benefits suggested some improvement ideas and design challenges. Table 7 shows the ideas respondents agreed with or mentioned most frequently. The table shows that the main design improvements that might get people to adopt micro-wind were: lower cost designs; roof-integrated systems; feedback on energy and money saved and visually attractive turbines. One non-adopter wanted '*an attractive, quiet wind turbine, that does not arouse objections from neighbours or planners*'. All these ideas provide challenges for engineers and designers. In particular there is active development of building integrated wind systems in which the building acts to channel the wind flow. Examples include Altechnica's patented design of roof with a wing-like concentrator, which creates a slot within which small turbines exploit an enhanced wind flow [26].

Solar photovoltaics

Household solar PV systems are not considered cost-effective at present given an average payback of 50 years or more, but if installed in the 9 million UK homes potentially suitable would save an estimated 2.5m tonnes carbon per year [27].

Only 12 people in our on-line survey had installed a solar PV system, mainly for environmental reasons (56%) or because they had the funds (43%). The satisfaction with solar PV is mixed and below that for solar thermal systems. Only a third of adopters were fairly or very satisfied, with about half of adopters unsure. This lack of satisfaction is probably due to not enough power being produced or available when required and the poor electricity grid feed-in tariffs available in the UK. Nevertheless, installing PV can have a beneficial influence on household energy consumption. Half the adopters said they were more concerned about saving energy after installing PV, while a quarter tried to use solar electricity when available, getting considerable satisfaction from doing so.

As for micro-wind, a third (probably the same people) had seriously considered this technology but decided against it. The main barriers to the installation of PV include capital cost (85%); too long payback (28%); insufficient output (28%); and connecting to the Grid (24%). One non-adopter stated, '*The cost per kWh hideously expensive; smaller systems would barely charge a car battery and to be useful would need to have a larger system integrated with 230V mains, with all the expense and issues with connecting to the grid. This type would require far too much roof space for me to consider*'.

Apart from economic measures (lower cost PV systems, new financing methods and better feed-in tariffs), the main improvements wanted by actual and potential adopters were: systems that give feedback on electricity generated and money saved, and long-term performance guarantees.

PV panels integrated with south facing windows, roof lights or conservatories were suggestions made by several respondents. Suitable semi-transparent PV cells exist but have yet to be used to any extent in domestic buildings because of their cost.

Table 8 shows the PV improvement ideas the on-line respondents chose or mentioned most frequently.

Table 8 Solar PV – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=16</i>	<i>Non-adopters (%) N=123</i>
Lower-cost PV systems.	11 (69%)	99 (80%)
Gives user feedback on money and energy saved	9 (56%)	56 (46%)
Guaranteed reliability, durability and payback.	5 (31%)	56 (46%)

Percentages are of on-line respondents who answered at least some questions on PV

Wood burning stoves

Wood burning stoves were the most widely adopted renewable energy device in our on-line survey (63 installations, 16% of sample). We did not distinguish simple wood burning stoves from automatic pellet stoves and boilers, but it is unlikely that (m)any of the automatic type were included. Wood stoves' popularity is due to their relatively modest cost, but also because they provide a relatively efficient real fire that adds to room décor.

Most (82%) wood stove adopters are very satisfied and two-thirds (65%) mentioned the pleasure of using a renewable fuel. Other benefits mentioned by about a third of adopters were lower fuel bills (37%) and greater energy efficiency (33%). The main problems cited by users were; more dust and dirt in the home (35%) and connecting the stove to radiators and/or the hot water system (28%). Also, there were rebound effects, due to the greater difficulty of controlling the output of wood stoves; some 60% of users said their stove heated one or more rooms to a higher temperature.

The main deterrents for non-adopters of wood stoves include: controlling heat output (43%); extra dust and dirt (41%); lack of fuel storage space (40%); labour of refuelling and ash removal (39%); and finding a suitable location (35%),

Table 9 shows the improvement ideas the on-line respondents chose or mentioned most frequently.

Table 9 Wood stove – improvements considered good ideas/would encourage adoption

<i>Improvement idea (on-line survey)</i>	<i>Adopters (%) N=63</i>	<i>Non-adopters (%) N=65</i>
Wood stoves that produce less smoke/pollution	33 (55%)	33 (48%)
Wood stoves with more controllable heat output.	22 (37%)	34 (49%)
Less frequent refuelling/ash removal	25 (42%)	28 (41%)
Wood stoves that produce less dust and dirt	25 (42%)	28 (41%)

Percentages are of on-line respondents who answered at least some questions on stoves

Interestingly, about half of both adopters and non-adopters wanted less polluting wood stoves, despite modern smokeless designs. Other desired improvements were for controllable, labour- and dirt-saving designs. Additional ideas and concepts suggested by survey respondents included:

- A multi-fuel stove to recycle combustible household waste, with pollution control;
- Ducts between rooms to transfer the heat from a stand-alone wood stove throughout the home.

6 CONCLUSIONS

This study surveyed the drivers and barriers to adoption of LZC technologies by two groups of mainly 'green' consumers and some benefits and problems experienced by users of these technologies. It also solicited these consumers' responses to ideas suggested by energy professionals and the research team for improving these products and systems plus the consumers' own improvement ideas, wants and solution concepts. The study suggests that information about, and feedback from, from actual and potential users can be useful for engineers, designers and manufacturers in guiding the R&D, specification and development, as well as the marketing, of LZC technologies.

While each LZC technology has different barriers to adoption and benefits and problems in use, there are some common drivers. In the on-line survey the drivers cited by the majority of adopters of energy efficiency measures were reducing fuel bills, saving energy and concern for the environment. Most online respondents adopted solar water heating (SWH), solar PV and micro-wind turbines for these

reasons, but some said they also adopted these renewables to make their environmental credentials visible. For wood burning stoves saving energy, money and the environment are again important, but they are mainly bought by people wanting an efficient real fire that adds to room decor. This suggests that an engineering design focus on the functional energy efficiency and fuel saving performance of these products is justified, but in some cases other design criteria such as aesthetic appeal also need to be considered.

However, the various barriers to adoption of each of the LZC technologies indicate that there are consumer needs and user problems not all of which are fully appreciated by designers and manufacturers. For example, those who rejected loft insulation did so mainly because the difficulties in using a loft covered with 270mm thick mineral fibre insulation for storage; while a few were deterred by the irritant effects of these insulation materials on some people's lungs. The biggest deterrent to installing new or additional CFLs was their size and appearance, followed by their incompatibility with existing fittings and/or dimmers and/or their colour temperature. High capital cost was the main reason for rejecting SWH and solar PV, but concerns about reliability and durability, and hence payback, were also barriers. These were also barriers to installing micro-wind turbines, but visual intrusion, noise and vibration were additional deterrents. Wood stoves were most often rejected because of difficulties in controlling their output and the extra dirt and labour they involve.

A key challenge for designers and engineers is therefore to offer lower cost, user-centred designs that offer high reliability and durability as well as saving energy. Designers need to think beyond individual LZC products or systems to how they interconnect with existing buildings and systems, overcoming problems such as a lack of compatibility between SWH systems and cold-fill appliances. Designers have a role in creating aesthetic LZC products and systems, overcoming the differences between people who dislike the visual impact of renewables, like solar panels and wind turbines, and those pleased with their symbolic display of environmental credentials.

The design of LZC technologies also influence how effective they are at saving energy when in use. For example, central heating controls that people find difficult to understand or adjust may not be used properly. Adopters of SWH, PV and micro-wind wanted control systems that indicated how best to use the system to minimize backup fossil fuel consumption.

The barriers to adoption, the problems experienced by users and the ideas suggested by consumers indicated a number of technical and design improvements that could improve the uptake and carbon saving effectiveness of different LZC technologies. Some of the most frequently requested ideas, requirements and concepts include:

- intelligent domestic heating controls that automatically optimise comfort and fuel use and provide feedback on energy consumption, heating times and room temperatures. (Such controls might form part of future home networking systems);
- dimmable CFLs and LEDs suitable for general lighting;
- building-integrated solar thermal, solar PV and micro-wind turbine systems;
- controls for solar water heating and PV systems that optimise solar energy utilisation, provide information on how best to use the system and feedback on money and energy saved. (Such controls might be linked to internet provided weather data);
- wood-burning stoves whose heat output is easier to control and distribute.

It was clear from respondents' comments and ideas and concepts such as the above that many were unaware of improvements and innovations in the design and technology of LZC products and systems that have already taken place. Where products are changing, consumers need to be kept informed by manufacturers and others of technical developments if they are not to reject technologies based on their outdated perceptions or experience. Likewise designers, engineers and manufacturers need to keep abreast of R&D in these technologies if they are not to develop and market designs that do not employ the latest improvements and innovations.

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